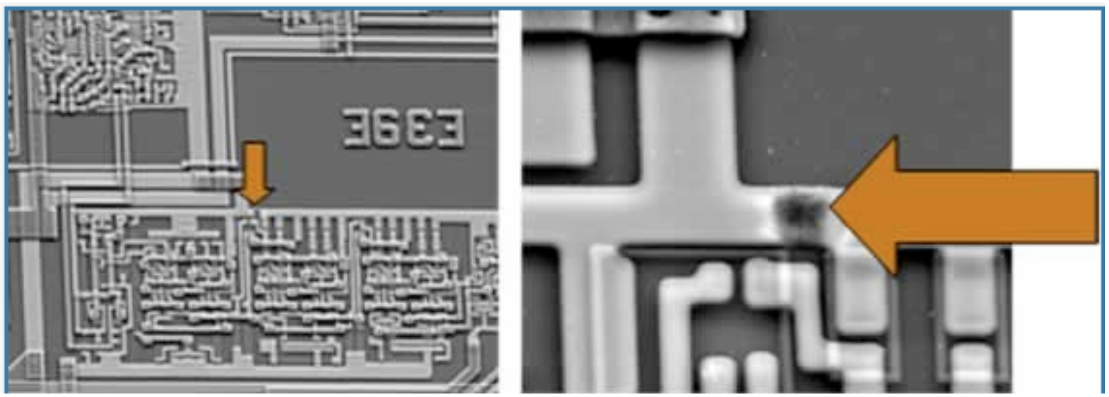
# ESD safety training

Donna Kubik
FNAL, April 2014

# But, static is not *always* fun!




It can lead to damage of sensitive semiconductor devices

# Outline of ESD safety training

- Slides on ESD safety
- Video about ESD safety

# Static charge

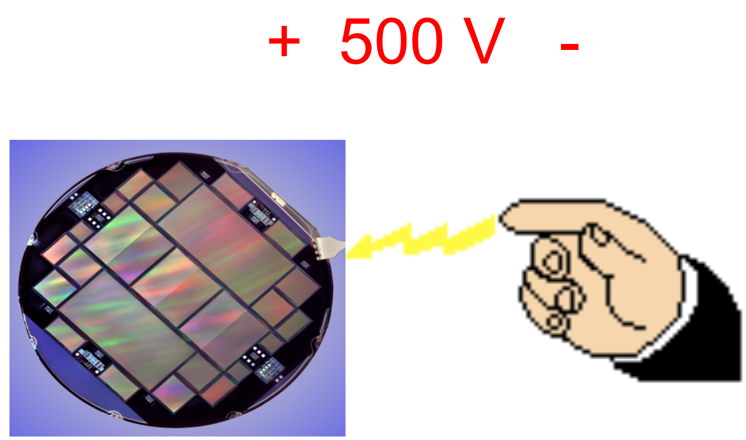
- Electrostatic electricity is an imbalance of positive and negative charges on the surface of objects.
- For example, a person can generate static charge while walking across the floor.
- The human body can charge to 100s or 1000s of volts.

\+ 500 V -

# Static charge

- For example, once charged, discharge from the finger tip to a CCD is possible, creating an electrostatic discharge (ESD) event.

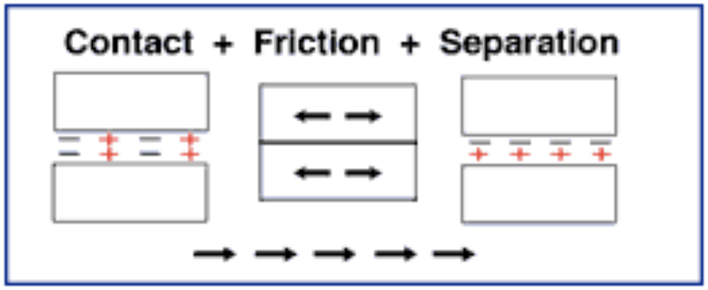
- The tiniest spark requires about 500 V, which more than 10 times more than a typical CCD gate dielectric can withstand before damage results.



How is an imbalance of charges created?

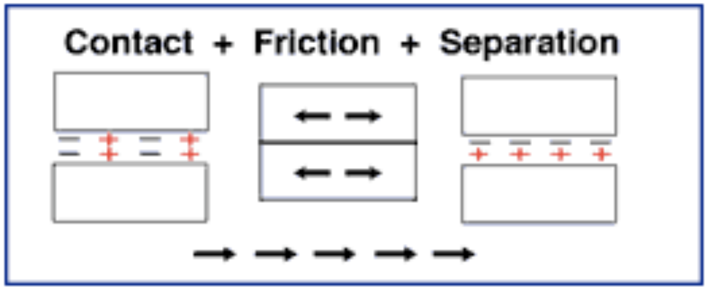
# Triboelectric effect

- How does the imbalance of charge get created?
- One very common way is to rub two objects together.
- If they are made of different materials and are both insulators electrons may be transferred from one to the other.
- The more rubbing, the more electrons move, and the larger the static charge that builds up.
- This is called the triboelectric effect
  - Tribo- means 'to rub'.



# Triboelectric effect

- Note: It is not the rubbing or friction that causes electrons to move.
- It is simply the contact between two different materials.
- Rubbing just increases the contact area between them.



# Triboelectric series

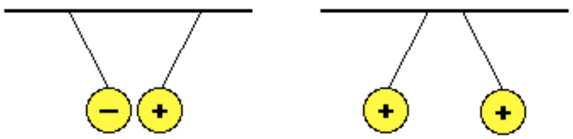
- When we rub two different materials together, which becomes positively charged and which becomes negative?
- Materials have been ranked according to their ability to hold or give up electrons.
- This ranking is called the triboelectric series.
- When 2 materials are rubbed together, the one higher on the list will give up electrons and become positively charged.

**TRIBOELECTRIC SERIES**

your hand
glass
your hair
nylon
wool
fur
silk
paper
cotton
hard rubber
polyester
polyvinylchloride plastic

# Why does your hair stand up after you put on a wool sweater?

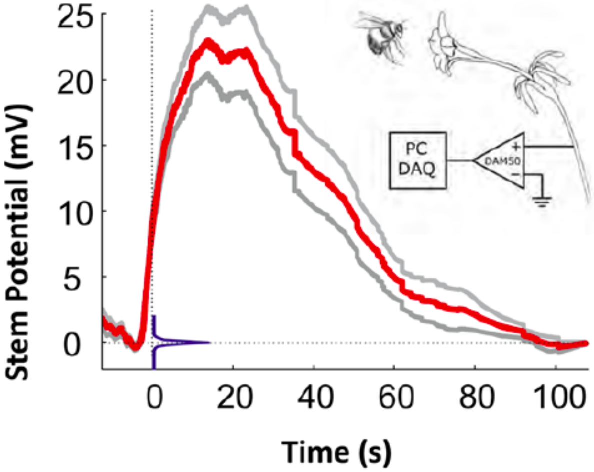
- When you put on your sweater, it rubs against your hair.
- Electrons move from your hair to the sweater. (Hair is above wool on the tribolectric series)
- Now each of the hairs has the same positive charge.
- Things with the same charge repel each other.
- So the hairs try to move away from each other.
- The farthest apart they can get is to stand up and away from all the other hairs.



# Does this happen to bees, too?

- As they travel through the air, bees lose electrons, accumulating a small positive electrical charge.
- Flowers have a natural negative electric charge and conduct electrons from the air to the ground.
- As a bee approaches a flower, a tiny electric field is created between plant and bee.
- A new study showed that the bee's landing actually changes the flower's electrical charge for a short period of time.
- The study's authors hypothesize that this change may signal to the next bee that the flower has just been visited and that its nectar is depleted.

My, what delicious electrons.




*Science*, 2013. DOI: 10.1126/science.1230883

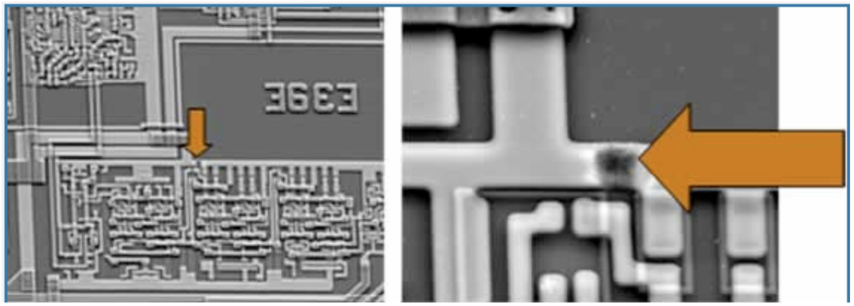
# Static charge and bees

- It’s unclear exactly how bees can sense these electrical fields, but it’s possible that their tiny hairs can bristle up when exposed to positive charges, just as our hair stands on end in response to static electricity.

*Science*, 2013. DOI: 10.1126/science.1230883

# Static charge and CCDs

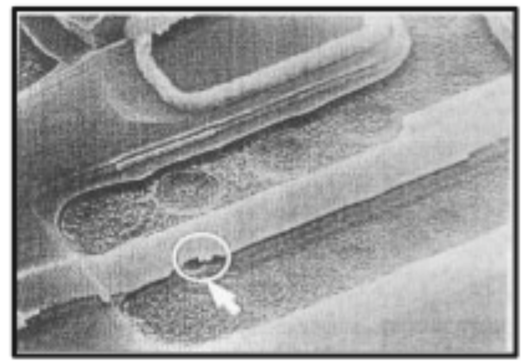
- The CCD is one of the most ESD-sensitive electronic components manufactured.
- Without ESD protection diodes, most scientific CCDs are susceptible to damage by electrostatic discharge.
- An ESD event can cause bus lines to melt, generate ESD craters, diode junction breakdown, or insulator failure.
- "Of these problems, dielectric damage is by far most prevalent."*



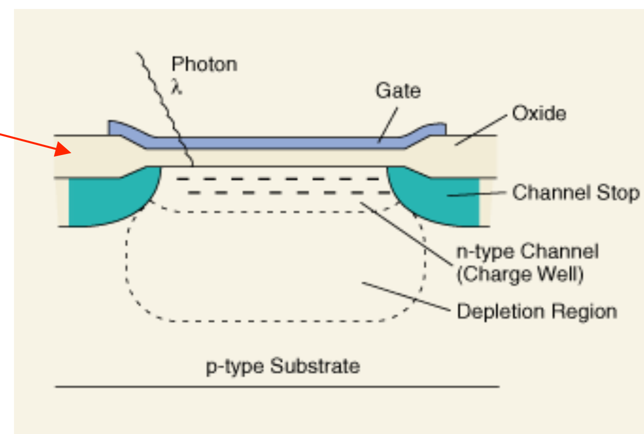

*Scientific CCDs*, J. R. Janesick

# Static charge and CCDs

- Although any semiconductor device can be damaged by a spark, MOS (Metal Oxide Semiconductor) devices are particularly susceptible.
- This is because the energy stored in the *gate-channel capacitance*, when it has been brought up to breakdown voltage, is sufficient to blow a hole through the delicate *gate oxide insulation*.*
- The gate oxide insulation is the *dielectric* mentioned in the previous slide.



Gate oxide damage to an input buffer




**The Art of Electronics*, Horowitz and Hill

# The need to practice ESD-safe procedures

- ESD gate protection helps, but it is not perfect (described in Appendix)
  - The most vulnerable (small) gates do get useful protection.
  - But very fast ESD spikes can still get through, and transistor drains are not protected.
- The CCDs used at Sidet have no on-chip ESD protection
  - DECam
  - DAMIC
  - CONNIE
  - MS_DESI
- Therefore, there is no substitute for careful procedure.

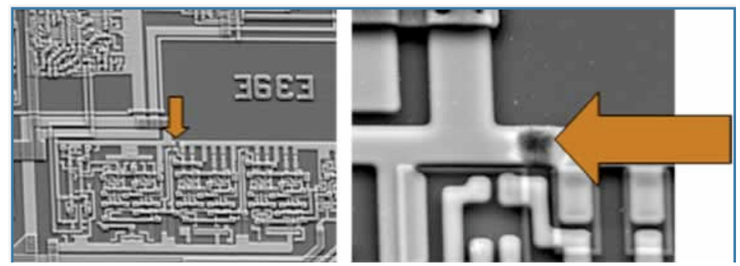
# The need to practice ESD-safe procedures

- Internal ESD protection networks of resistors and clamping diodes can
  - compromise performance
    - speed, noise
  - complicate device design
  - cause luminescence

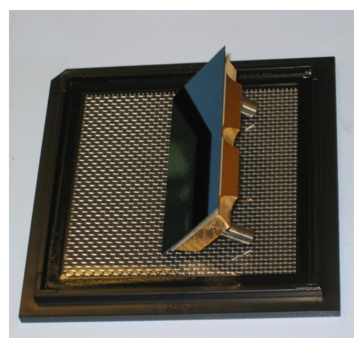
An example of amplifier luminescence can be seen in the upper left hand corner of this image. Luminescence could also be caused by a conducting diode.

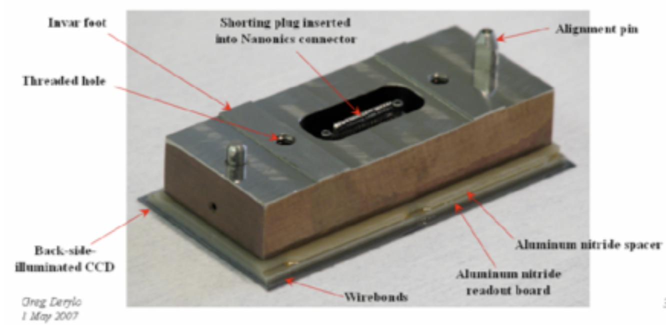
# Front-illuminated vs. back-illuminated CCDs

- For bare wafers or front-illuminated chips it is sometimes possible to view ESD damage under a microscope.



- However, DECam CCDs (and most research-grade CCDs) are back-illuminated, so, once packaged, it is not possible to see the damage.
  - Fault analysis is harder or impossible.





# The need to practice ESD-safe procedures

- There is also a concern about non-fatal ESD damage.
  - This could manifest itself as delayed failure or performance degradation, both of which are bad news.
- Again, there is no substitute for careful procedure.

# The need to practice ESD-safe procedures

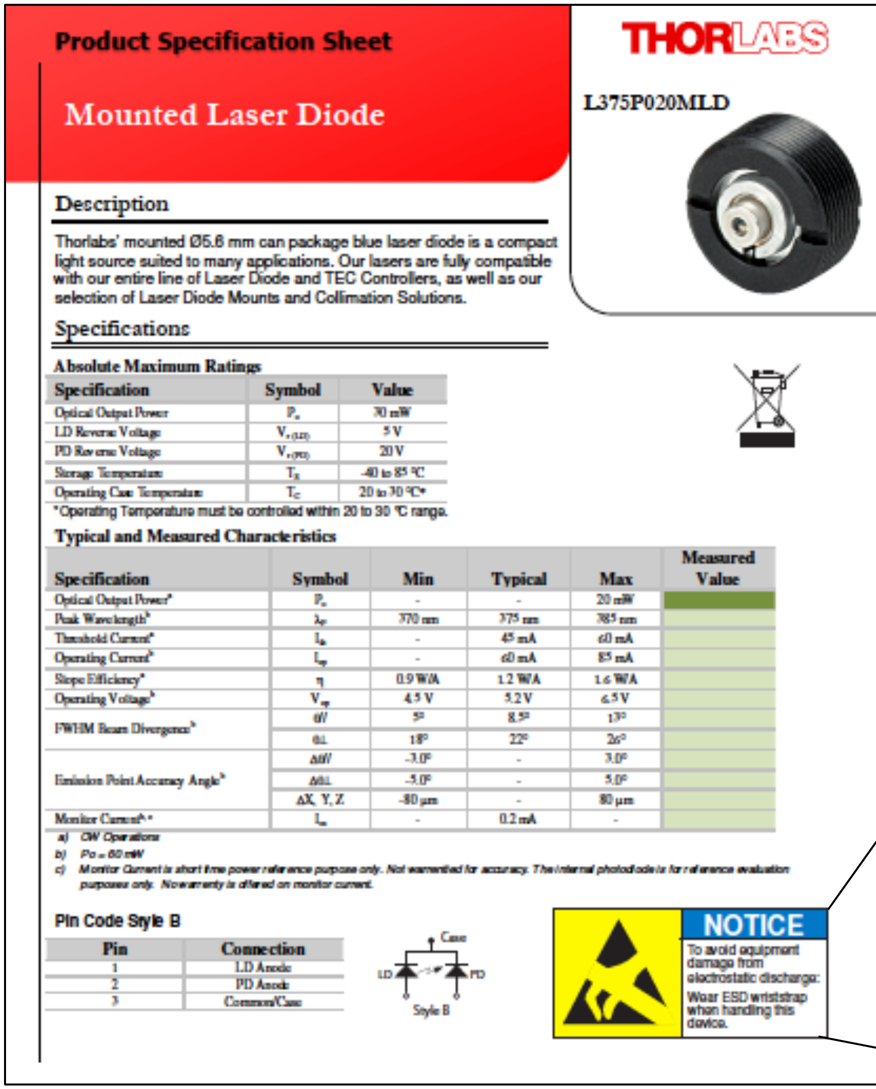
- Therefore, at Fermilab, ASIC designers often rely on the skill and care of the technicians to practice ESD safe procedures when packaging, installing, and testing devices rather than sacrificing performance or complicating the design by including internal protection.*

*Jim Hoff, Fermilab ASIC Designer

# Some examples of ESD-sensitive devices

# Laser diodes

# Laser diodes



**Product Specification Sheet**

**Mounted Laser Diode**

THORLABS

L375P020MLD

## Description

Thorlabs' mounted Ø5.6 mm can package blue laser diode is a compact light source suited to many applications. Our lasers are fully compatible with our entire line of Laser Diode and TEC Controllers, as well as our selection of Laser Diode Mounts and Collimation Solutions.

## Specifications

**Absolute Maximum Ratings**

| Specification | Symbol | Value |
|---|---|---|
| Optical Output Power | $P_o$ | 30 mW |
| LD Reverse Voltage | $V_{r(LD)}$ | 5 V |
| PD Reverse Voltage | $V_{r(PD)}$ | 20 V |
| Storage Temperature | $T_S$ | -40 to 85 °C |
| Operating Case Temperature | $T_C$ | 20 to 30 °C* |

*Operating Temperature must be controlled within 20 to 30 °C range.

**Typical and Measured Characteristics**

| Specification | Symbol | Min | Typical | Max | Measured Value |
|---|---|---|---|---|---|
| Optical Output Power[a] | $P_o$ | - | - | 20 mW | |
| Peak Wavelength[b] | $\lambda_p$ | 370 nm | 375 nm | 385 nm | |
| Threshold Current[a] | $I_{th}$ | - | 45 mA | 60 mA | |
| Operating Current[b] | $I_{op}$ | - | 60 mA | 85 mA | |
| Slope Efficiency[a] | $\eta$ | 0.9 W/A | 1.2 W/A | 1.6 W/A | |
| Operating Voltage[b] | $V_{op}$ | 4.5 V | 5.2 V | 6.5 V | |
| FWHM Beam Divergence[b] | $\theta_{//}$ | 5° | 8.5° | 13° | |
| | $\theta_{\perp}$ | 18° | 22° | 26° | |
| Emission Point Accuracy Angle[b] | $\Delta\theta_{//}$ | -3.0° | - | 3.0° | |
| | $\Delta\theta_{\perp}$ | -5.0° | - | 5.0° | |
| | ΔX, Y, Z | -80 µm | - | 80 µm | |
| Monitor Current[b,c] | $I_m$ | - | 0.2 mA | - | |

a) CW Operations
b) Po = 60 mW
c) Monitor Current is short time power reference purpose only. Not warrantied for accuracy. The internal photodiode is for reference evaluation purposes only. No warranty is offered on monitor current.

**Pin Code Style B**

| Pin | Connection |
|---|---|
| 1 | LD Anode |
| 2 | PD Anode |
| 3 | Common/Case |

Case

LD

PD

Style B

NOTICE

To avoid equipment damage from electrostatic discharge:

Wear ESD wriststrap when handling this device.


- Laser diodes are ESD-sensitive
- At Sidet
  - Used in SPDC experiment
  - CCD characterization

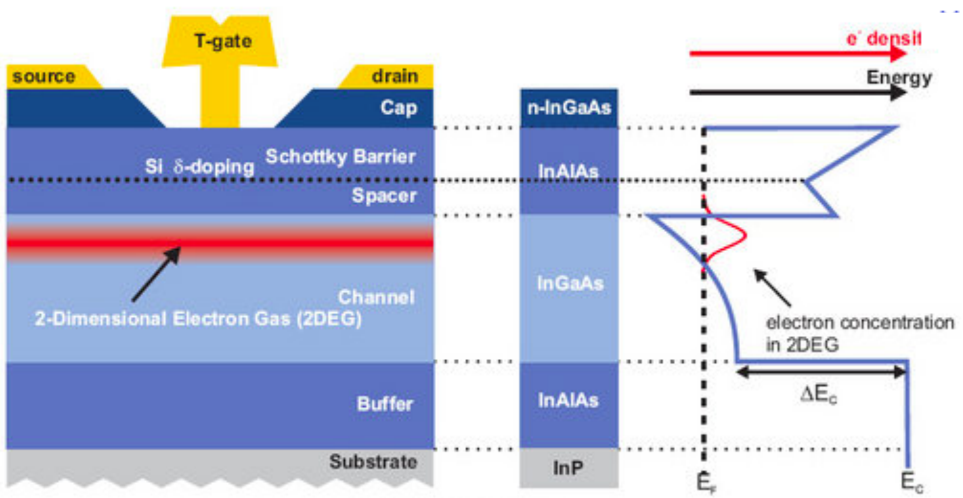
# Laser diode failure mechanisms*

- Over-voltage or over-current condition.
  - Electrical overstress: Failure of a laser diode’s P-N junction itself. A severe over-current or over-voltage power surge can cause localized heating and other harmful phenomena, which, under extreme conditions, can actually fracture the laser diode die.
  - Low-power laser diodes, that is, laser diodes whose optical output power is below around 200 mW, are particularly sensitive to ESD.
  - This is because they are designed to be inherently fast devices. Low-power laser diodes are often directly modulated and used for fiber-optic communication with data rates in the gigahertz range.
  - Thus the P-N junction and optical elements of a laser diode can react very quickly to changes in voltage or current.


*Source: http://www.lasorb.com/04_damage-mechanisms.htm

# HEMTs

# Transistors




Typical InP HEMT Structure

- Especially the newer InP-based High Electron Mobility Transistors (HEMTs)
  - QUIET
  - MKIDs
- Devices will typically start degrading with drain to gate voltage exceeding 2.5 V.
- Protect the drain at +1.8V and -.6 V and the gate at +- .6 V.
- There are typically two reasons for much lower breakdown than in either GaAs or Si devices.
  - Low Schottky barrier height for AlInAs
  - Lower avalanche breakdown in InGaAs

# 3D technology

# 3D technology at Fermilab

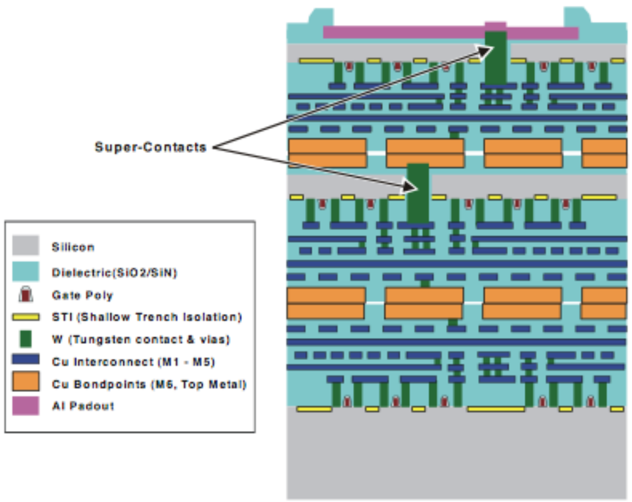



Figure 4 – Cross-section diagram of a finished three-wafer stack (with "via-middle" TSV)

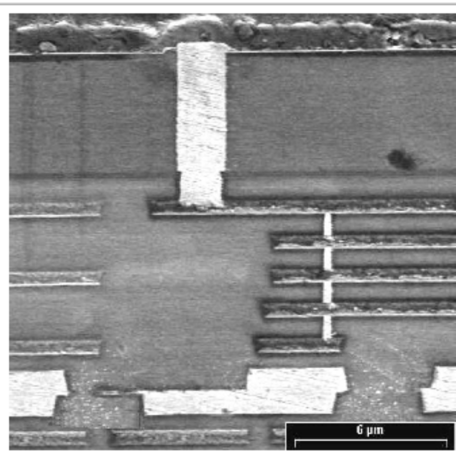



Figure 6 – SEM photo close-up of a Super-Contact.

- Stacking several silicon wafers and interconnecting them vertically with TSV (through-silicon vias) enables the creation of truly three-dimensional devices.
- Challenging ESD problems "antenna effects"
- Each layer needs an "antenna diode" to protect the devices during the assembly process.
- Need to test at intermediate steps.

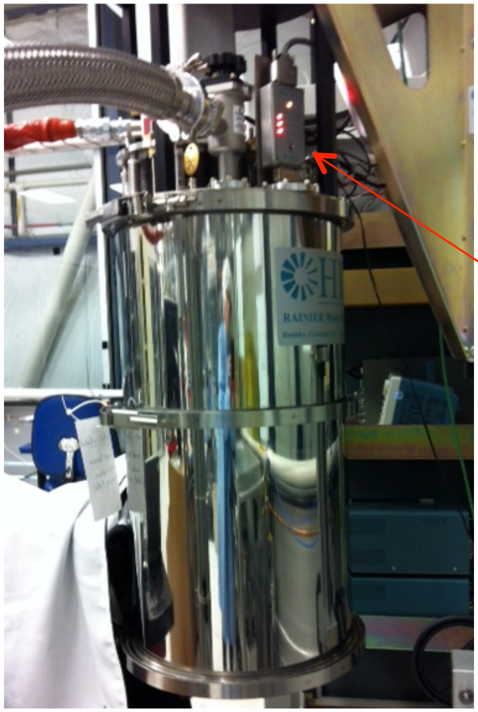
ADR

# Adiabatic Demagnetization Refrigerator (ADR)

- Always wear a wrist strap when working on or near the ADR, when the cryostat is both open and closed.
- In addition to sensitive devices that are part of the test setup, the heat switch controls are ESD-sensitive.

wrist
strap

ADR cryostat open

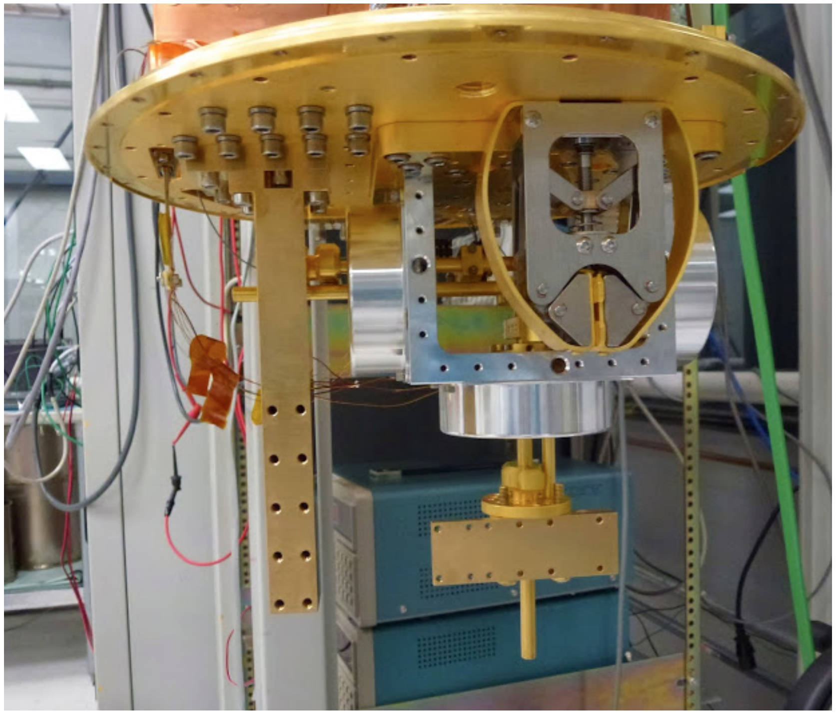


heat switch
control box

ADR cryostat closed

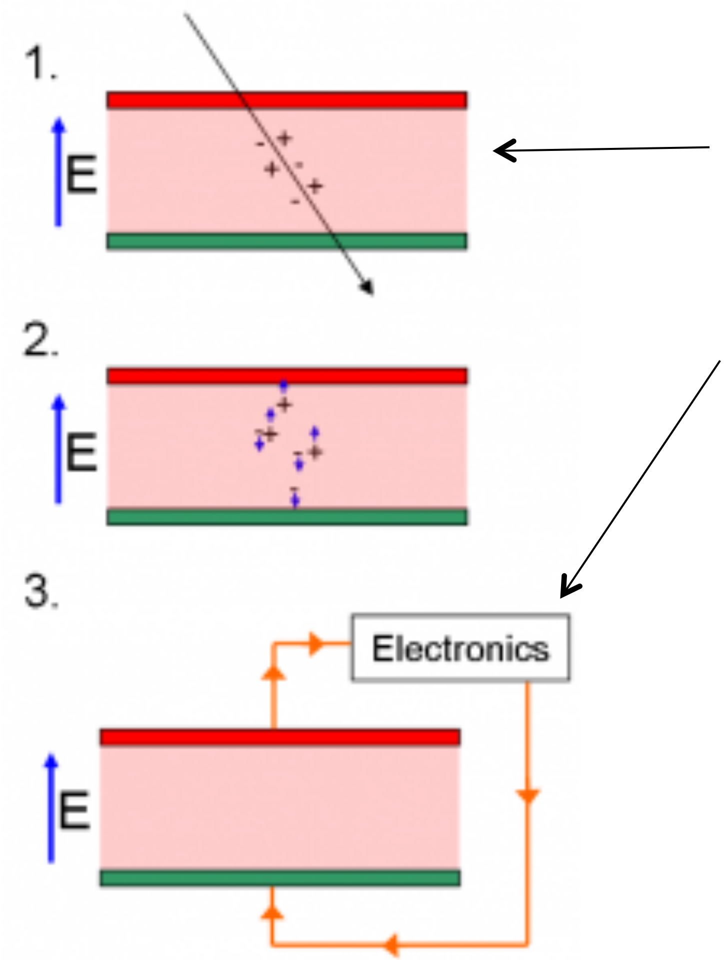
# ADR heat switch

Close-up view of ADR heat switch control box


ADR heat swtich

CMS

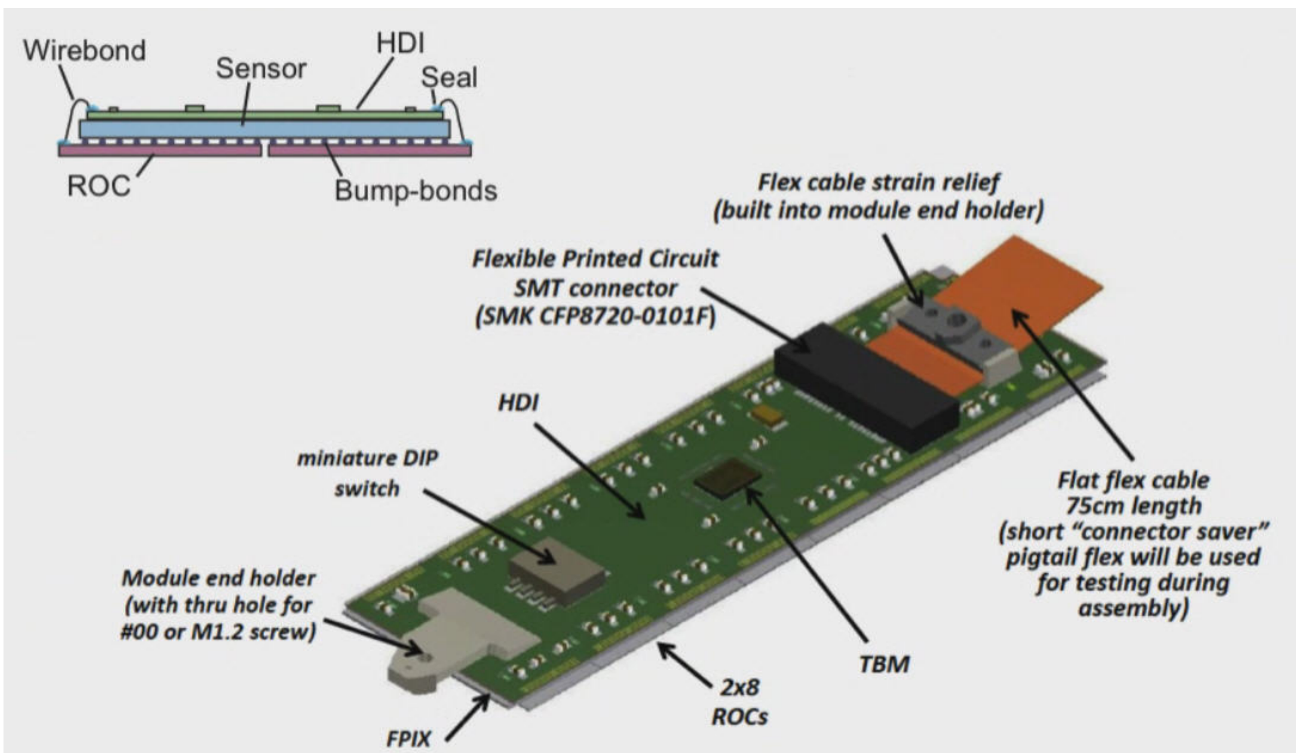
# CMS




- Sensors tend to be rather insensitive to ESD because of the thick oxides and large capacitance.
- But the ICs are quite sensitive.

# ESD-sensitive CMS electronics

- The ROC is most sensitive.
- Must also be careful handling the HDI, for it's connected to the ROC.



# CMS Pixel Specific Information

- Design of CMS pixel detector sensors and electronics very similar to that of original detector.
- Based on past experience, we do not expect to lose modules / sensors / electronics due to ESD if proper handling rules are followed.
- However we have recently damaged readout chips due to improper handling.
- Still have to understand exact mechanism that causes the damage and which parts are most sensitive to ESD.
- Expect readout chips to be more sensitive to ESD than sensors.

# When can damage happen?

- Handling of wafers (sensors, readout chips and ancillary electronics)
- Handling of individual electronics parts (HDIs populated with discrete components and TBM, individual readout chips)
- Handling of modules (sensor + readout chips + HDI)
- Some assembly steps done in industry, some at universities and Fermilab

# Minimizing damage risk

- Risks
  - Placing wafers on probe stations at multiple sites
  - Placing sensors and HDIs on gantry system at Purdue and Nebraska
  - Placing HDIs on probe stations for testing
  - Placing assembled modules on carrier boards
  - Connecting modules to test boards
  - Installing modules on half disks
  - Shipping / transporting / storing parts
  - Handling of individual chips

- In some cases we try to minimize risks by using protective covers. *Even in these cases you have to be properly connected to ground.*

# Other protective measures

- Parts stored in cabinets flushed with dry air
- Cabinets are grounded
- Static dissipative mats on the shelves
- Flush dry air in cold boxes during testing (and monitor humidity and temperature)

# Humidity

# Humidity helps

- If it is very humid, the charge imbalance will not remain for long time.
- If the humidity is high, the moisture coats the surface of the material, providing a low-resistance path for electron flow.
- This path allows the charges to "recombine" and thus neutralize the charge imbalance.
- If it is very dry, a charge can build up to extraordinary levels, up to tens of thousands of volts!

**Table I - Typical Electrostatic Voltage**

| | Electrostatic Voltages | |
|---|---|---|
| **Means of Static Generation** | 10-20 percent Relative Humidity | 65-90 percent Relative Humidity |
| Walking across carpet | 35,000 | 1,500 |
| Walking over vinyl floor | 12,000 | 250 |
| Worker at bench | 6,000 | 100 |
| Vinyl envelopes for work instructions | 7,000 | 600 |
| Common poly bag picked up from bench | 20,000 | 1,200 |

# Humidity

- Humidity and temperature are monitored and recorded 24/7 in *all* cleanrooms at Sidet.
- The alarm will sound if the relative humidity gets below 35%.
- If the alarm sounds, it can be silenced, but you should stop ESD-sensitive work until the humidity level is restored.


Humidity and temperature monitor

Humidity and temperature monitor in C100 cleanroom

# Humidity is not enough

- As the table shows, triboelectric charging persists, even at high relative humidity.
- Humidity control does limit the triboelectric charging process, but humidity does not eliminate the need for all of the conventional safeguards!

**Table I - Typical Electrostatic Voltage**

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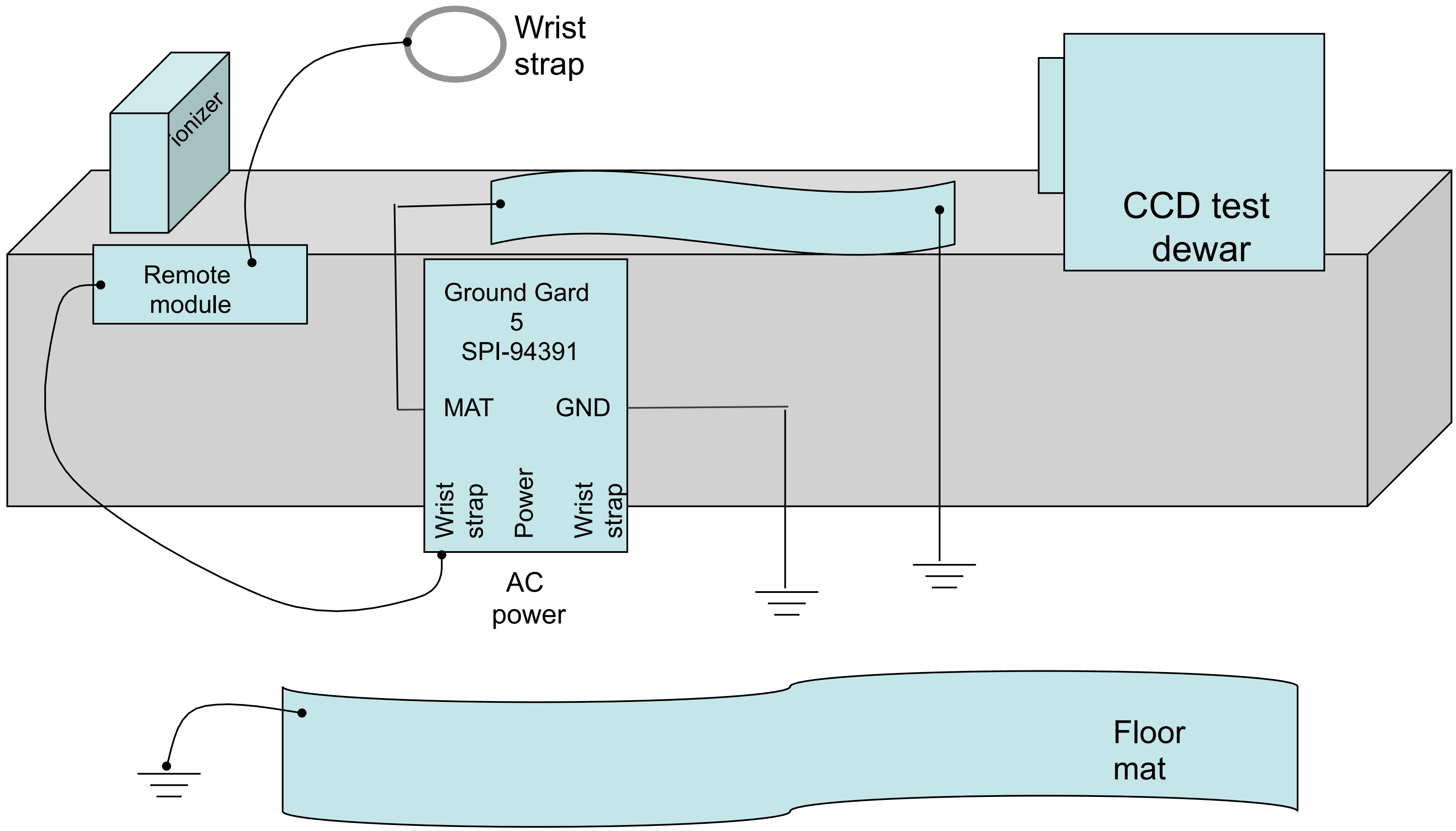
| Common poly bag picked up from bench | 20,000 | 1,200 |

# The need to practice ESD-safe procedures

- There is no substitute for careful procedure.
- Therefore we must follow all ESD safety procedures very carefully to minimize the chance of damaging the CCDs:
  - Constant monitoring of grounding
  - ESD-safe garments
  - ESD-safe workspace

# Continuous ESD monitoring



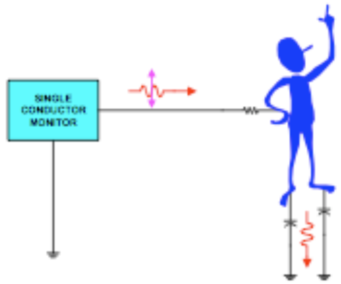
# Wrist straps

# Types of continuous wrist strap monitors

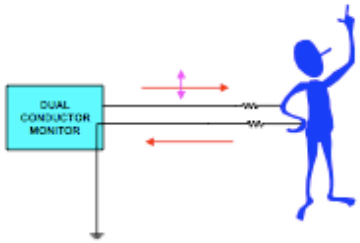
- There are several systems of continuous wrist strap monitors.

- The most common are
  - Single conductor monitors
  - Dual conductor monitors

**SINGLE CONDUCTOR MONITOR**

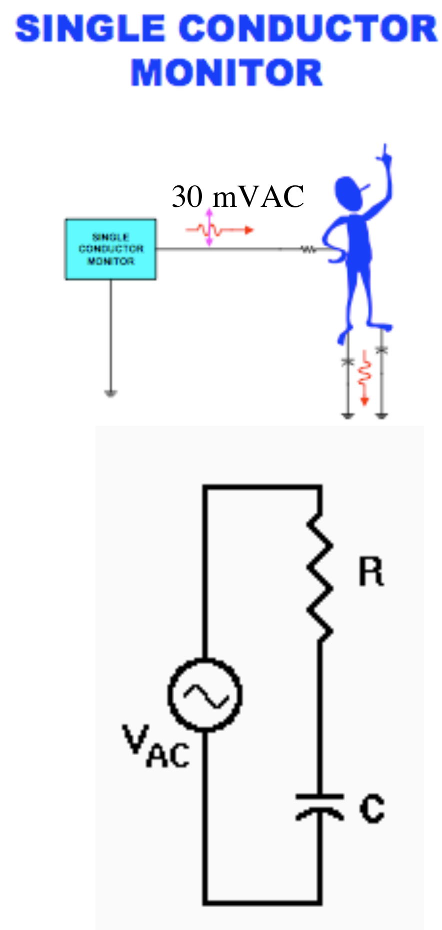



**DUAL CONDUCTOR MONITOR**



# Single conductor continuous wrist strap monitors

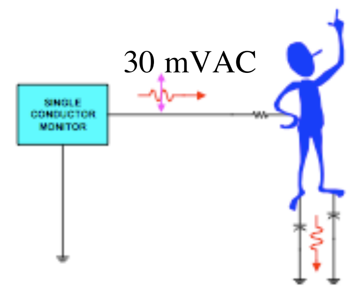
- The wrist strap monitors we currently use fin most areas are single conductor monitors
- A person can be thought of as a plate of a capacitor with the other plate being ground.
- The “plates” are separated by an insulator as shoes and mats.
- The person and the resistors built into the wrist strap and connecting cords form the resistor.

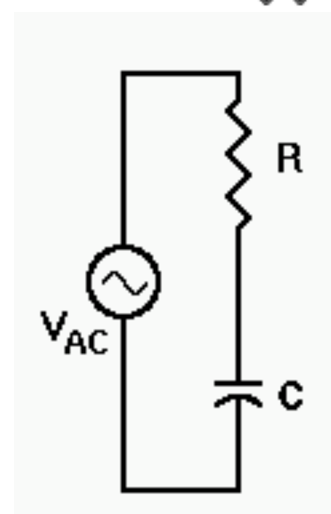


# Single conductor continuous wrist strap monitors

- A 30 mVAC current applied to this circuit provides a way to measure whether the circuit is complete.
- Any break will cause a higher impedance that can be used to trigger an audible alarm.

**SINGLE CONDUCTOR MONITOR**



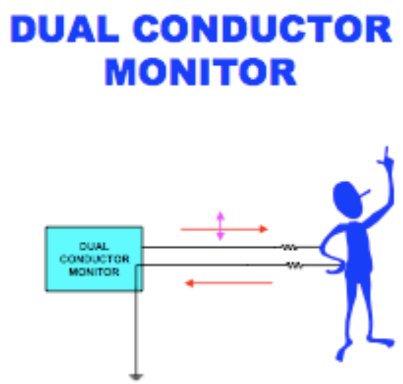



# Dual conductor continuous wrist strap monitors

- A tiny pulsed DC current applied to this circuit provides a way to measure whether the circuit is complete.

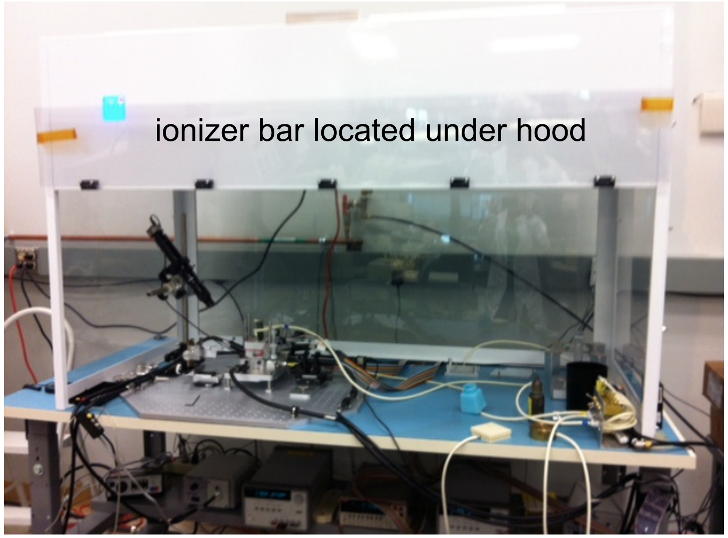
- The voltage at your wrist is < 300 mVDC.

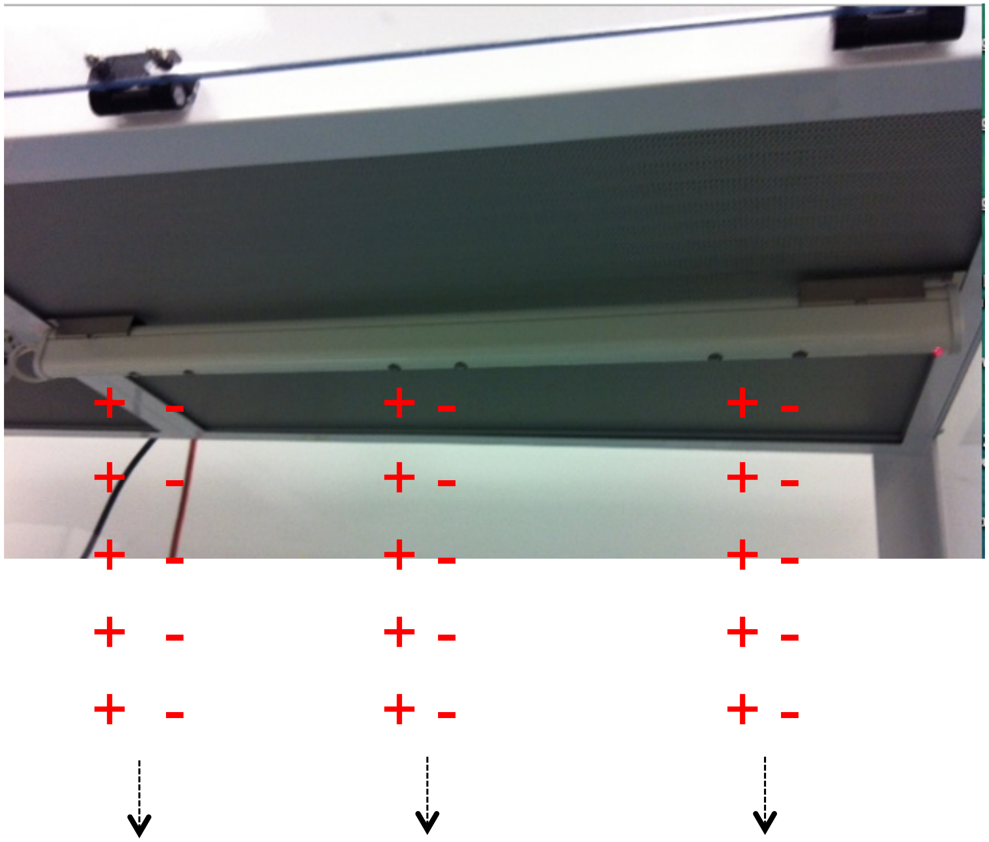
- Any break will trigger an audible alarm.



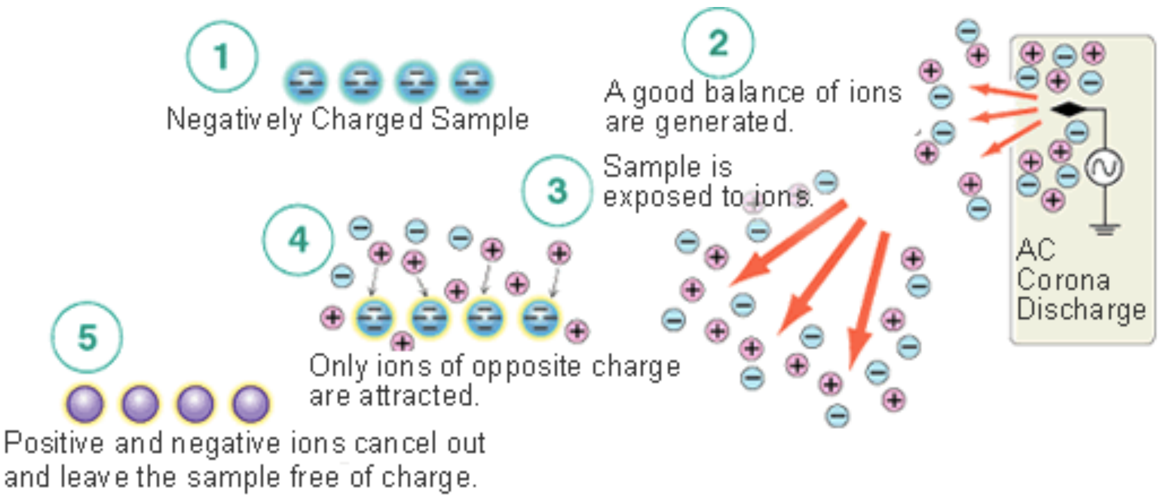
# Ionizers

# Ionizer bar



# Benchtop ionizer




# ESD-safe garments

# ESD-safe(r) garments

- New garments met ESD-safe specifications much better
- They have a higher percentage of carbon thread and dissipate static more quickly.

C100 cleanroom garments

New cleanroom garments in C100 cleanroom

# Test garments

- Test
  - Surface resistance (ohms/square)
  - Point to point resistance (ohms)
  - Ability to dissipate static

New cleanroom garments in C100 cleanroom

# Test equipment

- Test
  - Surface resistance (ohms/square)
  - Point to point resistance (ohms)
  - Ability to dissipate static


Megohmmeter


Static locator

# Class 100 cleanroom

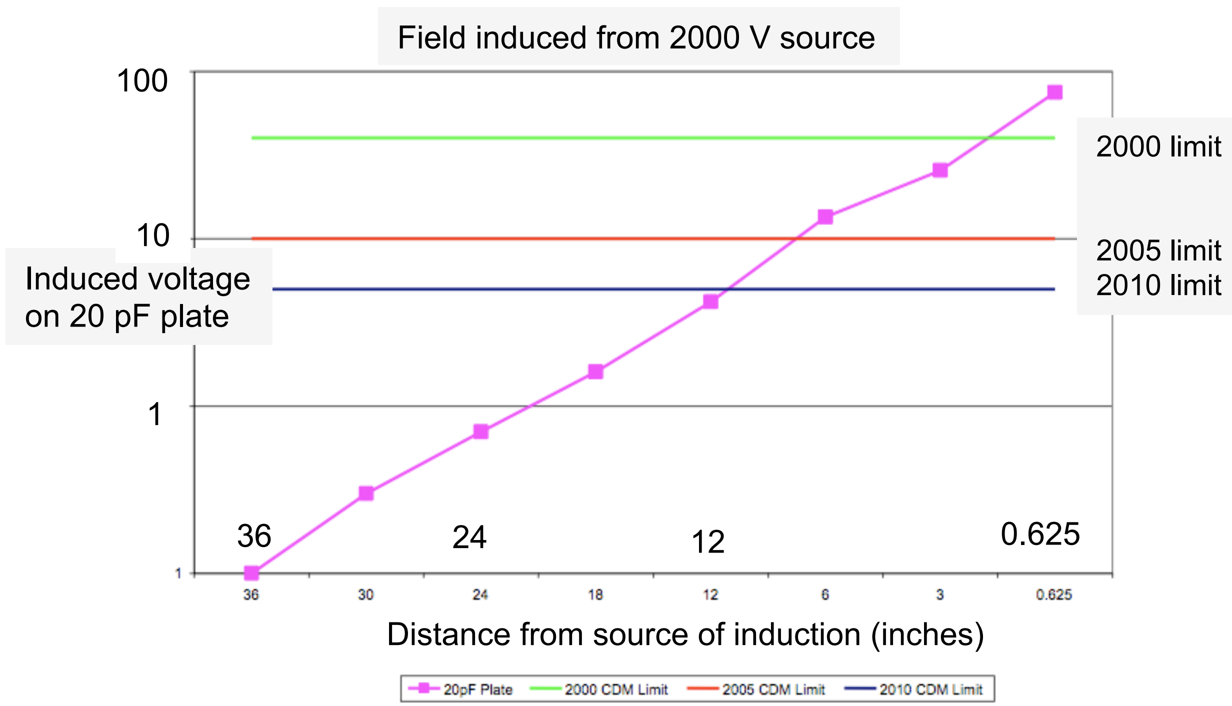
- Test
  - Surface resistance of walls, floor, ceiling, and table mats (ohms/ square)
  - Grounding (ohms)

Charging by induction

# Charging by induction

- Field Induced Charge Device Model damage from an electrostatic field occurs when a charged item is brought into close proximity to an ESD sensitive device and the device is then grounded while in the presence of the field.

- *Keep unsafe materials and unprotected people at least 3 feet away from ESD sensitive devices.*



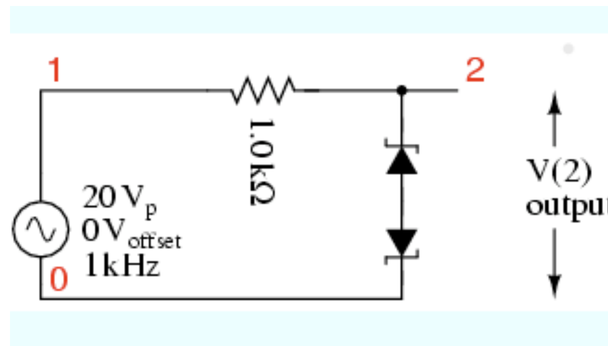
Video

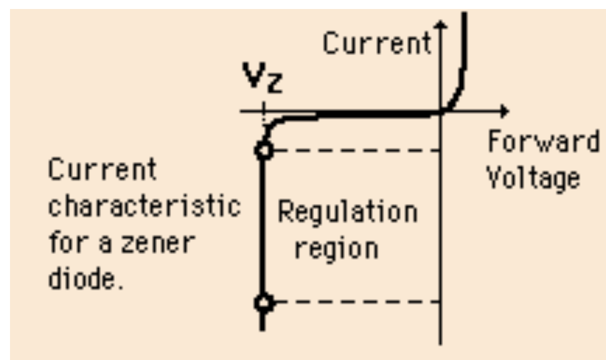
# Appendix

# An example of ESD protection for CCDs

# An example of ESD protection for CCDs

- e2v (a commercial CCD vendor) manufactures CCDs for astronomical applications
  - e2v CCDs are used on CFHT, HST, SWIFT, and many more ground and space based telescopes
- They use on-chip back-to-back zener diodes for ESD protection on all the gates
  - This works for bipolar signals
- This is one of several techniques that can be used to help minimize susceptibility to ESD damage
- A more-detailed description of the operation of this protection circuit is in the Appendix.



# Back-to-back zeners

- For example, assuming a zener breakdown voltage of 10 V, back-to-back zener diodes will clip both +/-10 V.
  - For a positive half-cycle, the top zener is reverse biased, breaking down at the zener voltage of 10 V.
  - The lower zener drops approximately 0.7 V since it is forward biased.
  - Thus, a more accurate clipping level is 10+0.7=10.7V.
- Similar negative half-cycle clipping occurs at -10.7 V.